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The Optical Gravitational Lensing Experiment. The OGLE-III Catalog of Variable Stars. I. Classical Cepheids in the Large Magellanic Cloud*

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ABSTRACT

We present the first part of a new catalog of variable stars (OIII-CVS) compiled from the data collected in the course of the third phase of the Optical Gravitational Lensing Experiment (OGLE-III). In this paper we describe the catalog of 3361 classical Cepheids detected in the ≈ 40 square degrees area in the Large Magellanic Cloud. The sample consists of 1848 fundamental-mode (F), 1228 first-overtone (1O), 14 second-overtone (2O), 61 double-mode F/1O, 203 double-mode 1O/2O, 2 double-mode 1O/3O, and 5 triple-mode classical Cepheids. This sample is supplemented by the list of 23 ultra-low amplitude variable stars which may be Cepheids entering or exiting instability strip.

The catalog data include *VI* high-quality photometry collected since 2001, and for some stars supplemented by the OGLE-II photometry obtained between 1997 and 2000. We provide basic parameters of the stars: coordinates, periods, mean magnitudes, amplitudes and parameters of the Fourier light curve decompositions. Our sample of Cepheids is cross-identified with previously published catalogs of these variables in the LMC. Individual objects of particular interest are discussed, including single-mode second-overtone Cepheids, multiperiodic pulsators with unusual period ratios or Cepheids in eclipsing binary systems.

We discuss the variations of the Fourier coefficients with periods and point out on the sharp feature for periods around 0.35 days of first-overtone Cepheids, which can be explained by the occurrence of 2:1 resonance between the first and fifth overtones. Similar behavior at $P \approx 3$ days for 1O Cepheids and $P \approx 10$ days for F Cepheids are also interpreted as an effect of resonances between two radial modes. We fit the period–luminosity relations to our sample of Cepheids and compare these functions with previous determinations.

Key words: *Cepheids – Stars: oscillations – Magellanic Clouds*

*Based on observations obtained with the 1.3-m Warsaw telescope at the Las Campanas Observatory of the Carnegie Institution of Washington.

1. Introduction

The Optical Gravitational Lensing Experiment (OGLE) is a wide-field sky survey originally motivated by search for microlensing events (Paczyński 1986). The observing strategy of the project is to regularly monitor brightness of about 200 million stars in the Magellanic Clouds and Galactic bulge in the time-scales of years. A by-product of these observations is an enormous database of photometric measurements, which can be used for selecting long lists of newly discovered variable stars.

The OGLE project yielded a wealth of information about variable stars. The second phase of the survey, conducted between 1997 and 2000, resulted in catalogs of thousands Cepheids, RR Lyr stars, eclipsing binaries and long period variables in the Magellanic Clouds. Moreover, the huge catalogs of variable sources found in the OGLE-II fields in the Magellanic Clouds (Żebruń *et al.* 2001) and in the Galactic bulge (Woźniak *et al.* 2002) were released. In this paper we present the first part of the OGLE-III Catalog of Variable Stars (OIII-CVS) – the catalog containing virtually all variable stars in the fields regularly observed by OGLE since 2001 with the Warsaw telescope at Las Campanas Observatory, Chile.

Classical Cepheids (δ Cep stars, type I Cepheids), as the primary distance indicator, are among the most important variable stars. The Large Magellanic Cloud (LMC) is one of the most fundamental extragalactic targets of modern astrophysics, because it is our nearest non-dwarf neighbor galaxy. For this reason we begin the OIII-CVS with the catalog of classical Cepheids in the LMC.

Large number of variable stars in the LMC, including classical Cepheids, were discovered by Leavitt (1908). However, the first period derivation and the plot of the period–luminosity (PL) diagram for 40 LMC Cepheids was made by Shapley (1931). In 1955 the periods of 550 classical Cepheids in the LMC were published (see Shapley and McKibben Nail 1955 for the bibliography). Then, a considerable survey for LMC Cepheids was done by Woolley *et al.* (1962). The catalog prepared by Payne-Gaposchkin (1971) on the basis of Harvard photographic plates contained about 1100 Cepheids in the LMC. After hiatus, a number of Cepheids in the LMC were also discovered by Hodge and Lee (1984), Kurochkin *et al.* (1989), van Genderen and Hadiyanto Nitihardjo (1989) and Mateo *et al.* (1990). In the late 1990's very large catalogs of Cepheids were published as a by-product of gravitational microlensing surveys: EROS (Beaulieu *et al.* 1995, Afonso *et al.* 1999), MACHO (Welch *et al.* 1997, Alcock *et al.* 1999b) and OGLE-II (Udalski *et al.* 1999d, Soszyński *et al.* 2000).

The catalog described in this work contains the largest sample of classical Cepheids detected to date in the LMC and, likely, in any other environment. Almost 1000 objects are new identifications. Double-mode Cepheid sample presented in this paper is three times more numerous than the largest sample presented so far. We also show individual objects of particular interest, like triple-mode Cepheids, Cepheids with non-radial pulsations, Cepheids in eclipsing binary systems, etc.

The paper is organized as follows. In Section 2 we describe how the observations were obtained and reduced. Section 3 gives the details about the process of Cepheid selection. In Section 4 we describe the catalog itself. We compare our sample with previously published catalogs of the LMC classical Cepheids in Section 5. In Section 6 we discuss the Fourier coefficients as a function of periods. In Section 7 we fit the period–luminosity relations. Finally, Section 8 summarizes the paper.

2. Observations and Data Reduction

The photometric data were obtained with the 1.3-m Warsaw telescope located at Las Campanas Observatory in Chile. The observatory is operated by the Carnegie Institution of Washington. The telescope is equipped with the "second generation" camera consisting of eight SITe 2048×4096 CCD detectors with 15 μm pixels what corresponds to 0.26 arcsec/pixel scale. The gain of the chips is adjusted to be about 1.3 e^-/ADU with the readout noise from 6 to 9 e^- depending on the chip. For details of the instrumental setup we refer to Udalski (2003).

Observations of 116 OGLE-III fields covering 39.7 square degrees of the LMC started in July 2001. The data presented in this paper were collected up to March 2008. In the future, photometry provided with the catalog will be supplemented by observations obtained after this date, up to the end of the third phase of the OGLE survey.

The photometry was obtained using Difference Image Analysis (DIA) technique (Alard and Lupton 1998, Alard 2000, Woźniak 2000), which is able to perform in dense stellar fields considerably better photometry than the traditional PSF-fitting programs. We emphasize that even though there are small gaps between the chips of the CCD mosaic, our final DIA photometry pipeline (Udalski *et al.* 2008a) provides photometry of stars from the entire fields, because, due to imperfections of the telescope pointing, the regions between the chips are also observed from time to time. Thus, the completeness of the catalog is practically not limited by the lack of observations in the gaps between the chips, although the smaller number of points at the edges of the fields sometimes may decrease the efficiency of variability search.

About 90% of observations were taken in the I photometric band closely resembling standard filter. The remaining frames were observed in the V bandpass. The data were calibrated to the standard system using hundreds of thousands stars observed during the OGLE-II project (1997–2000) and common with the OGLE-III observations. The procedure of calibration of the data and astrometric transformations were described by Udalski *et al.* (2008a). The accuracy of the photometric calibrations is better than 0.02 mag, while equatorial coordinates in the catalog have uncertainties of about $0\overset{\prime\prime}{.}1$.

Photometry error bars derived by the DIA package were known to be under-

estimated. Here we corrected the error bars using technique derived for OGLE-II LMC microlensing events search and described in detail in Wyrzykowski *et al.* (in preparation). In brief, the method compares observed photometric scatter of constant stars in a given field with their mean error bars and fits the coefficients of relation between original and corrected error bar: $\sigma_{\rm corr} = ((\gamma\sigma)^2 + \varepsilon^2)^{1/2}$. For OGLE-III data γ and ε were derived independently for each field and CCD chip. On the average $\gamma = 1.204$ and $\varepsilon = 0.0046$ in the I band. In V filter: $\gamma = 0.996$ and $\varepsilon = 0.0035$.

For the central 4.5 square degrees of the LMC the OGLE-II photometry (Szymański 2005) was available. When it was possible we tied both datasets to obtain the time base of observations covering 12 years. For each star we shifted the OGLE-II photometry to agree with the mean OGLE-III magnitudes, however in some peculiar Cepheids with variable mean magnitudes more advanced procedure should be applied.

Our sample contains 47 Cepheids with no *I*-band data in the OGLE-III database, usually due to exceeding the CCD saturation limit (which is about $I = 13$ mag). In a few cases our photometric techniques failed in the centers of the clusters. For 16 of these objects the OGLE-II *I*-band photometry is available, where the level of saturation was slightly higher ($I = 12.5$ mag). Note, that the OGLE-III photometry for the brightest stars is sometimes more noisy due to exceeding the saturation limit.

Luckily, most of these bright or cluster stars have observations in the V filter, because our *V*-band data for classical Cepheids saturate for periods longer than ≈ 50 days. Only for the five longest-period Cepheids, neither I nor *V*-band photometry are available. However, even for these stars we could measure periods and shapes of their light curves, because in the DIA technique every bright variable star produces a number of artificial objects in the closest neighborhood that mimic the variability of this bright star. This is because the DIA method does not subtract the profiles of the neighboring objects while doing photometry. We used these artificial light curves for measuring periods of the long-period Cepheids. The calibrated *VI* photometry for brightest stars in the LMC will be published soon, when the shallow survey conducted on the Warsaw telescope will be finished. At that moment we will be able to supplement our catalog with the data for the brightest Cepheids.

3. Selection of Cepheids

3.1. Single-Mode Cepheids

The search for classical Cepheids in the LMC was preceded by a massive period search performed using supercomputers at the Interdisciplinary Centre for Mathematical and Computational Modeling of Warsaw University (ICM UW). We searched for periodicity all 32 million stars in the LMC using program FNPEAKS by Z. Kołaczkowski. We tested the range of frequencies from 0.0 to 24.0 cycles

per day, with a frequency step of 0.0001. For each star the ten highest peaks in the power spectrum were recorded with appropriate amplitudes and S/N parameters. Then, the third order Fourier series was fitted to each light curve folded with the dominant period, the function was subtracted from the data, and the procedure of period searching was repeated on the residual data.

The first criterion used for the identification of classical Cepheids in our data were positions in the PL diagrams. We tested stars located not only strictly in the PL relations for classical Cepheids, but also in wide region above and below these sequences, including type II Cepheids which will be published in a forthcoming paper. We used PL diagrams in various wave bands: – I, V, Wesenheit index, and near-infrared K band from the 2MASS project (Cutri *et al.* 2003).

Tens of thousands light curves selected in this manner were subsequently subjected for a visual inspection. During the careful inspection the variables were divided into pulsating-like stars, eclipsing binaries and other variable objects. Then, the candidates for pulsating variables were filtered according to the $(V-I)$ colors. We removed from the list objects bluer than $(V-I)=0.2$ mag and redder than $(V-I)=1.8$ mag, however we carefully checked, if the rejected objects are not real classical Cepheids extraordinarily reddened or with erroneous photometry.

Stars which remained on the list were a mixture of various pulsating variables crossing the classical instability strip: classical Cepheids, type II Cepheids, anomalous Cepheids, RR Lyr stars from the Galaxy and the LMC and High Amplitude δ Sct stars (HADS). The long period classical Cepheids were relatively easy to distinguish, due to their narrow PL relations and characteristic shapes of the light curves. However, in the short-period domain (for $P<3$ days and in particular for $P<1$ days) the PL sequences overlap with various types of pulsating variables. Separation of classical Cepheids from other pulsators was based mainly on the shapes of their light curves. We will discuss this problem in the next part of the OIII-CVS.

Our data show that first-overtone classical Cepheids and HADS follow the same PL relation, with no discontinuity. Thus, our distinction between both groups is arbitrary, being a matter of convention. To define limiting period we used double-mode pulsators, which we detected in significant number among classical Cepheids and HADS. In the Petersen diagram (*i.e.,* the ratio of periods *vs.* logarithm of the longer period plot, Petersen 1973) the stars pulsating simultaneously in the fundamental mode and first overtone (F/1O) are naturally separated into two groups, with the gap between (fundamental mode) periods in the range 0.4–1 days. Among pulsators with the first two overtones excited (1O/2O) we detected only one group with the shortest first overtone period of about 0.24 days. Thus, $P_1=0.24$ days was taken for the first-overtone pulsators as a boundary between HADS and classical Cepheids. For the fundamental-mode Cepheids we cut our sample of δ Cep stars at $P_0=0.995$ days, *i.e.,* the shortest F period of double-mode F/1O Cepheids (with exception of a peculiar object OGLE-LMC-CEP-0083). We notice, that only a few

pulsating-like variables with shorter periods were found on the continuation of the fundamental-mode Cepheids PL relation, but the shapes of their light curves were considerably different than for F Cepheids. The preliminary distinction between fundamental (F) and first overtone (1O) classical Cepheids was done using their positions in the $W_I - \log P$ diagram, but the final classification utilized the Fourier parameters R_{21} and ϕ_{21} (see Section 6). The exemplary light curves of single-mode Cepheids from the whole range of periods and luminosities covered by OGLE are presented in Fig. 1.

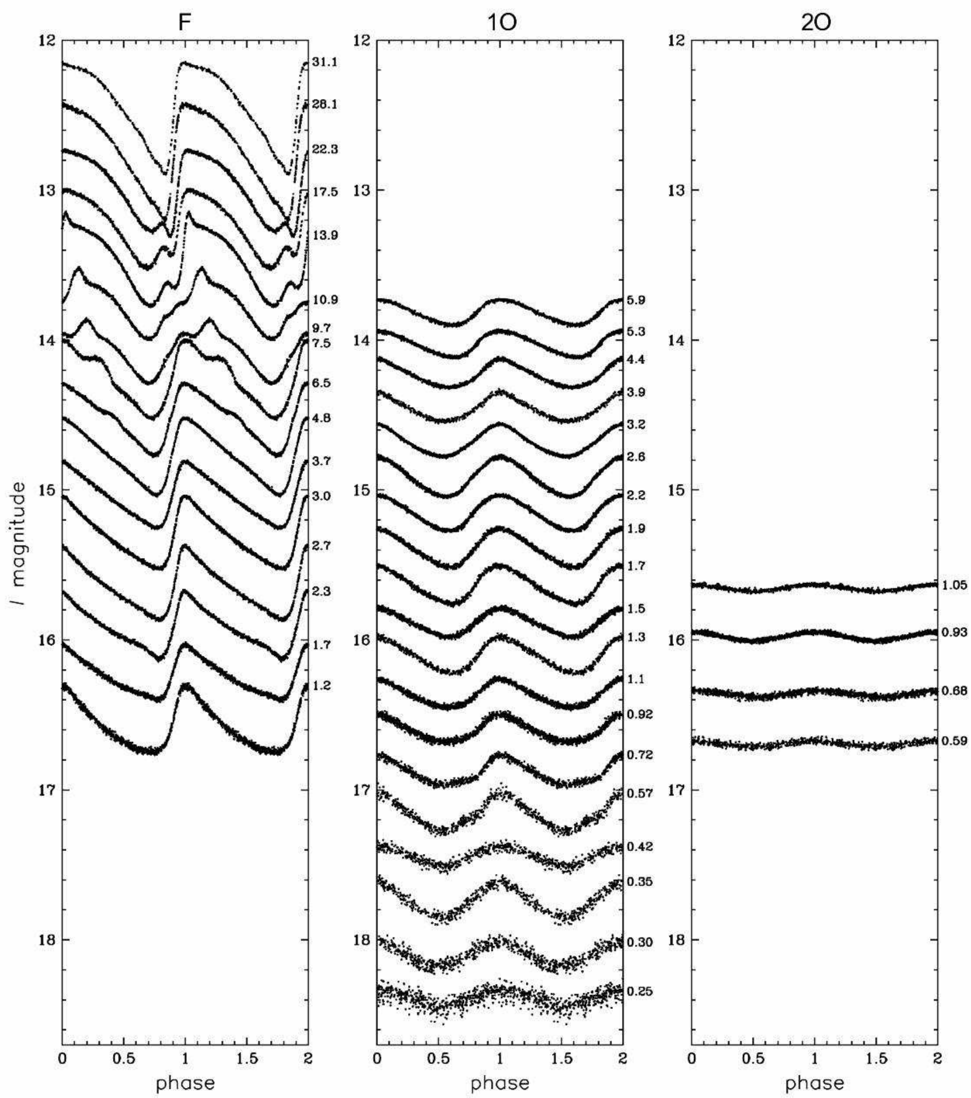

Fig. 1. Illustrative light curves of fundamental-mode (*left panel*), first-overtone (*middle panel*) and second-overtone (*right panel*) Cepheids. Small numbers at the right side of each panel show the rounded periods in days of the light curves presented in panels.

3.2. Second-Overtone Cepheids

Classical Cepheids pulsating solely in the second overtone are very rare but astrophysically interesting objects, because they can be used as an independent test of pulsational and evolutionary models (Antonello and Kanbur 1997, Bono *et al.* 2001). There is only one potential candidate for the pure 2O Cepheid in the Galaxy – V473 Lyr (HR 7308 – Burki *et al.* 1986). Alcock *et al.* (1999a) undertook a search for single-mode 2O Cepheids in the LMC using double-mode Cepheids pulsating in the first and the second overtones as templates. They separated both modes in beat Cepheids and studied the 2O variations. Singly-periodic second overtone Cepheids should have nearly sinusoidal light curves, small amplitudes and mean luminosities slightly higher than 1O Cepheids of the same periods. In the color–magnitude diagram these stars should occupy the blue edge of the instability strip. Alcock *et al.* (1999a) proposed one candidate for 2O Cepheid in the LMC.

Udalski *et al.* (1999b) followed the same strategy as MACHO group for Cepheids in the Small Magellanic Cloud (SMC). Theoretical investigations suggest that metal-poor environments favor Cepheids pulsating purely in the second overtone mode. As a result, Udalski *et al.* (1999b) found 13 firm candidates for 2O pulsators – the largest such sample detected to date.

We started a search for singly-periodic second overtone Cepheids using all LMC stars in our database. We selected stars with S/N of periods larger than 9 and located just above the period – *I*-band magnitude relation for 1O Cepheids (spreading from the upper edge of the PL sequence to 0.75 mag above this line). Then, the light curves were visually inspected and obvious eclipsing binaries were rejected. At this stage we noticed a distinct group of stars located at the blue edge of the instability strip ($0.2 < (V-I) < 0.6$ mag). From this group we removed a few pulsating variables with asymmetrical light curves which we classified as blended RR Lyr stars. The last criterion of our selection was the ratio of amplitudes in the V and I bands, what allowed us to remove a couple of ellipsoidal variables from our list. Ellipsoidal modulation is mainly a geometrical effect, so the amplitudes in two filters are very similar, while for Cepheids, the V-band amplitudes are larger than for I band by a factor of about 1.7.

In total 14 objects passed our selection criteria, all of them in the period range 0.58–1.2 days and in the low-amplitude domain. It is a very homogeneous group which delineates additional PL sequence located above the relation of the first-overtone pulsators. The shapes of the light curves (see Fig. 1 for examples) are of the same type as in the 2O Cepheids found by Udalski *et al.* (1999b), with Fourier parameter R_{21} smaller than 0.1. The MACHO candidate for 2O Cepheid in the LMC (Alcock *et al.* 1999a) is also on our list.

3.3. Multiperiodic Cepheids

Double-mode or beat Cepheids pulsate simultaneously in two radial modes – usually fundamental mode and first overtone (F/1O) or first and second overtones

(1O/2O). Very few such objects had been known before the large microlensing surveys era. The situation changed when the MACHO project announced the discovery of 45 beat Cepheids in the LMC (Alcock *et al.* 1995), increased later to 73 objects (Welch *et al.* 1997). Based on the data collected during the OGLE-II project the OGLE group published samples of 93 double-mode Cepheids in the SMC (Udalski *et al.* 1999a) and 76 such stars in the LMC (Soszyński *et al.* 2000).

The search for double-mode Cepheids in the LMC was carried out in two manners. First, using periods determined for all stars in the LMC we calculated the ratios of the principal periods found in two iterations of the period searching and plotted the Petersen diagram. Then, we selected all the stars located close to the expected position of the double-mode pulsators in the LMC. These stars were visually inspected, and objects with clear double-periodic signal were left on the list. This way not only beat Cepheids were selected, but also double mode δ Sct and RR Lyr stars, which will be presented in the next parts of the OIII-CVS.

Second, additional search for double-mode variables was performed for all previously selected Cepheids. Each light curve was fitted by a Fourier series with a number of harmonics minimizing the χ^2 per degree of freedom and the function was subtracted from the observational data. The residuals were searched for other periodic signals and, if detected, such a candidate was marked for visual inspection. We discovered several new double-mode Cepheids and a number of other multi-periodic variables, such as Cepheids with periodicities very close to the dominant periods, Cepheids in eclipsing binary systems, Cepheids blended with other variable stars.

Fig. 2 shows the Petersen diagram for multi-mode Cepheids in our list. Black points represent the Cepheids pulsating in two radial modes. It is worth emphasizing that our sample of double-mode Cepheids covers much larger range of periods than presented to date. We especially point out for one long-period F/1O Cepheid OGLE-LMC-CEP-1082 with fundamental-mode period equal to 7.86 days, however connected with exceptionally low amplitude of pulsations. In the list of F/1O double-mode Cepheid we included also one double-periodic pulsator, OGLE-LMC-CEP-0083, with exceptionally short periods (0.581 d and 0.440 d) and the period ratio placing this object in the Petersen diagram somewhat above the line connecting F/1O double-mode Cepheids and HADS. On the other hand, we found a considerable number of short-period 1O/2O Cepheids, with the first-overtone periods even as short as 0.24 days. It is remarkable that in the range of 1O periods 0.5–0.75 days double-mode pulsators are significantly more common than single-mode Cepheids.

We also performed a search for triple mode Cepheids. Three new stars of that type were discovered in addition to two already known triple-mode Cepheids in the LMC (Moskalik *et al.* 2004). The analysis of these stars is presented in the paper by Soszyński *et al.* (2008). In the same work we also announced the discovery of two double-mode Cepheids pulsating simultaneously in the first and third overtone

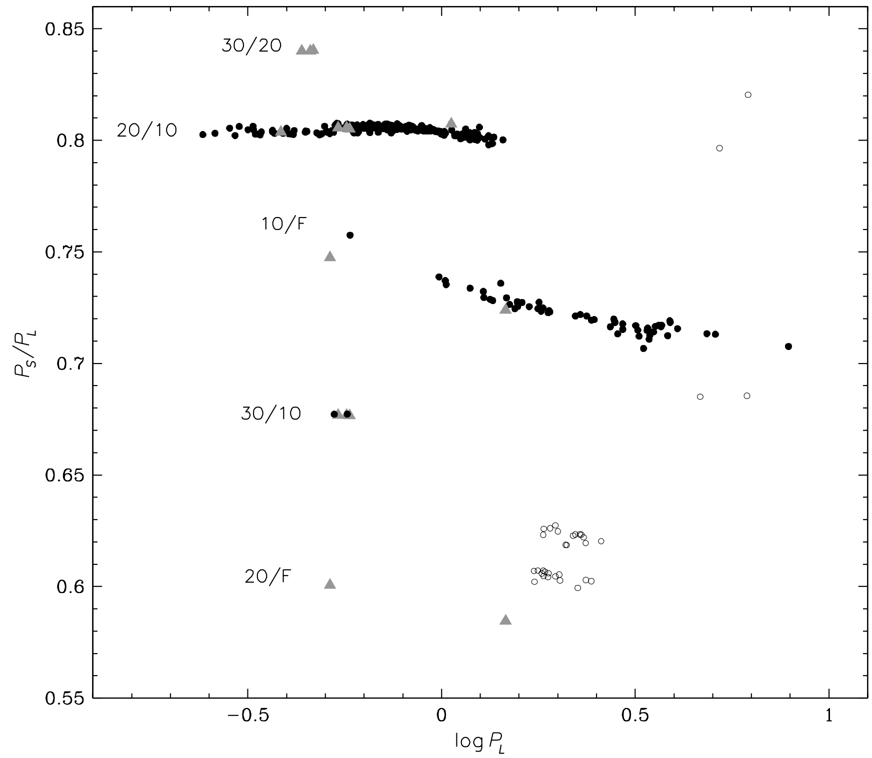

Fig. 2. Petersen diagram for multiperiodic Cepheids in the LMC. Solid dots represent double-mode (F/1O, 1O/2O and 1O/3O) Cepheids, grey triangles show triple-mode Cepheids (three points per star) and empty circles show selected other stars with significant secondary periods.

modes. This is a new class of double-mode Cepheids.

During the search for multiperiodicity we detected a significant number of Cepheids with the secondary periods very close to the primary ones. Such ratios of periods close to 1 are usually connected with a long-term amplitude and/or phase modulation, and, by analogy to RR Lyr stars, these objects are called Blazhko Cepheids. Using our simple analysis we detected such behavior in about 4% of F Cepheids, 28% of 1O and in the same fraction of 2O single-mode Cepheids, 18% of F/1O beat Cepheids, and 36% of 1O/2O double-mode Cepheids. For single-mode pulsators this is somewhat larger fraction than detected by Moskalik and Kołaczkowski (2008b) in the OGLE-II data, what can be explained by the longer time span of our new photometry. Among double-mode Cepheids, the fraction of non-radial pulsators seem to be comparable with values determined by Moskalik and Kołaczkowski (2008a,b).

We also noticed in the Petersen diagram a number of objects with period ratios that do not match any known phenomena. Especially numerous group was found for period ratios of 0.60–0.63 days and (longer) periods in the range 1.7–2.6 days. It is interesting that the longer periods are always related to the first overtone mode, while the shorter periods are connected to low-amplitude variations. A few such

Cepheids were recently listed by Moskalik *et al.* (2008b) who suggested that such a behavior is connected with a kind of non-radial oscillations. In our Petersen diagram these stars seem to follow two sequences, with period ratios in the ranges 0.60–0.61 and 0.62–0.63.

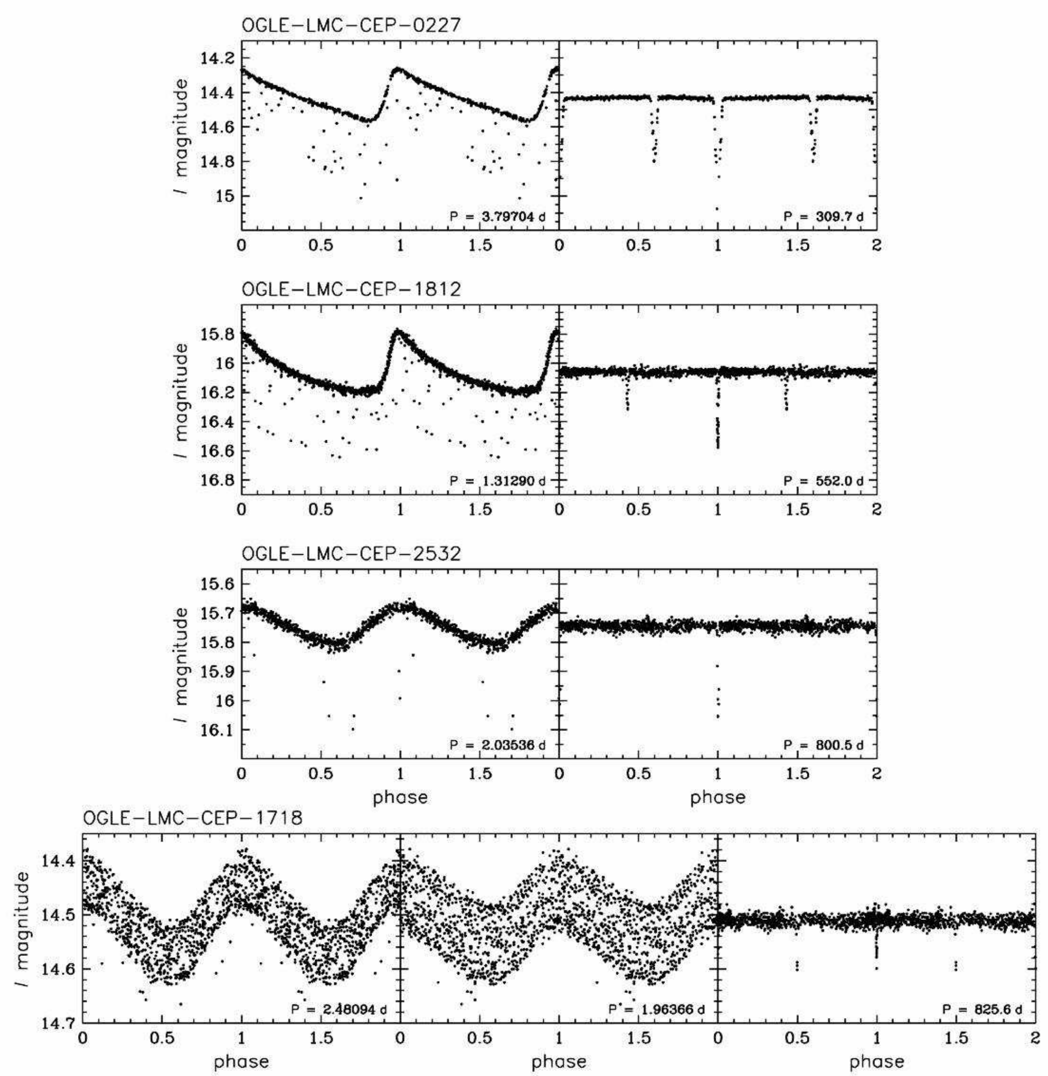

Fig. 3. Light curves of Cepheids with additional eclipsing variability. *Left panels* show the original photometric data folded with the Cepheid periods. *Right panels* show the eclipsing light curves after subtracting the Cepheid component. In the case of OGLE-LMC-CEP-1718 two Cepheid light curves are presented.

As a by-product of searching for double-mode pulsators we detected three Cepheids with eclipsing modulation imposed on the pulsational light curves: OGLE-LMC-CEP-0227, OGLE-LMC-CEP-1812 and OGLE-LMC-CEP-2532. Only the last one was already reported by Udalski *et al.* (1999d – LMC_SC16 119952).

Light curves of these stars are presented in Fig. 3. Cepheids with eclipsing variations are of particular interest, because, if they are physical binaries with the pulsating star as one of the components, they can be used for direct determination of the mass and radius of Cepheid variable. In some cases it is possible to distinguish between physically related objects and optical binaries. If the eclipses are caused by a nearby star which is not resolved by standard photometry, we should have found the shift in centroid positions measured during eclipse and out of eclipse. No such shift was found for these objects. Four other Cepheids – OGLE-LMC-CEP-0388, OGLE-LMC-CEP-2052, OGLE-LMC-CEP-2095, and OGLE-LMC-CEP-3037 – are suspected to be in eclipsing binary systems. They are brighter than other Cepheids with the same periods, but we detected only a few points in each of these stars that can be associated with potential eclipses.

We also draw attention to the extremely interesting object OGLE-LMC-CEP-1718, which is a system consisting of two first overtone Cepheids with eclipses visible every 412.8 days. This object was discovered by Alcock *et al.* (1995 – MACHO*05:21:54.8-69:21:50) and noticed by Udalski *et al.* (1999d), but the eclipses were overlooked. Fig. 3 shows the light curves of this object. Besides, we also detected two already known double Cepheids (Alcock *et al.* 1995): OGLE-LMC-CEP-0571 and OGLE-LMC-CEP-0835.

There are also several Cepheids in our sample exhibiting additional short-period and low-amplitude eclipsing modulation certainly caused by blending. There are also Cepheids with additional variability of other types, *e.g.*, cataclysmic-like changes, semiregular variations, long secondary periods, etc. The majority of these cases can be explained as an effect of physical or optical binarity with other variable star.

Since the time base of the OGLE-III observations is 2400 days, and for the merged OGLE-II and OGLE-III data is longer than 4000 days, our data offer a possibility of studying various long-term effects in the Cepheids – period changes, amplitude and phase modulation, or mean magnitude changes. The full study of the period changing Cepheids will be published in the forthcoming paper (Poleski 2008, in preparation).

4. Catalog of Classical Cepheids in the LMC

In total 3361 classical Cepheids were found in the LMC OGLE-III fields. The sample consists of 1848 fundamental-mode, 1228 first-overtone, 14 second-overtone, 61 double mode F/1O, 203 double mode 1O/2O, 2 double-mode 1O/3O, 2 triple-mode F/1O/2O and 3 triple-mode 1O/2O/3O classical Cepheids.

In addition we prepared a list of 23 low amplitude variables which can be related to classical Cepheids, because they lie in the vicinity of Cepheids in the color–magnitude and PL diagrams. Such low-amplitude Cepheids are expected by the evolutionary models as pulsators entering or exiting the instability strip.

Table 1

Exemplary part of the ident.dat file

Cepheid ID	OGLE-III ID Field	No	Mode	RA [J2000.0]	DEC [J2000.0]	OGLE-II ID	MACHO ID	ASAS ID	GCVS ID LMC...	Other designation
...										
OGLE-LMC-CEP-0931	LMC118.5	23110	F	05:05:57.39	−68:26:17.9	LMC_SC13_125152			V1015	HV2305
OGLE-LMC-CEP-0932	LMC116.6	12576	1O	05:05:59.04	−67:20:42.4					
OGLE-LMC-CEP-0933	LMC115.6	14990	F	05:05:59.19	−66:47:15.0				V1001	HV13058
OGLE-LMC-CEP-0934	LMC121.2	30142	F	05:06:00.15	−70:27:22.4		23.4151.25		V1041	HV2330
OGLE-LMC-CEP-0935	LMC119.6	101320	F	05:06:00.89	−69:06:17.1	LMC_SC13_74156		050601-6906.3	V1032	HV893
OGLE-LMC-CEP-0936	LMC118.6	29152	F	05:06:01.13	−68:37:38.5	LMC_SC13_111968				
OGLE-LMC-CEP-0937	LMC117.7	49519	F/1O	05:06:02.74	−68:06:02.3		19.4186.876			
OGLE-LMC-CEP-0938	LMC118.7	77581	F	05:06:05.75	−68:41:52.1	LMC_SC13_106993			V1019	HV13022 LMV1696
OGLE-LMC-CEP-0939	LMC115.7	14854	F	05:06:05.98	−66:59:43.9				V1013	HV13057
OGLE-LMC-CEP-0940	LMC121.2	36964	F	05:06:07.06	−70:26:08.8		23.4151.27		V1048	DV81
OGLE-LMC-CEP-0941	LMC115.5	14135	F	05:06:07.13	−66:37:49.3					
OGLE-LMC-CEP-0942	LMC121.4	39539	1O	05:06:08.12	−70:11:16.7					
OGLE-LMC-CEP-0943	LMC122.1	3754	F	05:06:08.88	−71:15:26.1			050609-7115.4	V1059	HV2338
OGLE-LMC-CEP-0944	LMC121.3	7423	1O	05:06:11.39	−70:25:45.7		23.4151.40			
OGLE-LMC-CEP-0945	LMC115.5	17550	F	05:06:14.81	−66:40:45.9			050615-6640.8	V1022	HV2294
OGLE-LMC-CEP-0946	LMC118.8	85656	1O	05:06:14.89	−68:51:56.7	LMC_SC13_160626	1.4175.14			
OGLE-LMC-CEP-0947	LMC117.8	26519	1O	05:06:14.94	−68:19:03.1	LMC_SC13_197484				
OGLE-LMC-CEP-0948	LMC118.7	34808	1O	05:06:16.43	−68:47:20.5	LMC_SC13_165223	1.4176.34			
OGLE-LMC-CEP-0949	LMC118.7	77545	F	05:06:16.89	−68:40:33.7	LMC_SC13_173745	19.4178.3		V1040	HV895
OGLE-LMC-CEP-0950	LMC119.1	81	1O	05:06:18.33	−69:31:47.9	LMC_SC12_133630				
OGLE-LMC-CEP-0951	LMC115.5	14063	F	05:06:18.53	−66:38:44.7				V1029	W48
OGLE-LMC-CEP-0952	LMC115.5	14065	F	05:06:19.60	−66:35:47.8					
OGLE-LMC-CEP-0953	LMC122.4	139	1O	05:06:22.14	−70:48:05.3		23.4146.20			
OGLE-LMC-CEP-0954	LMC117.6	51980	F	05:06:22.87	−67:58:33.5		19.4188.23		V1042	HV5571 LMV779
OGLE-LMC-CEP-0955	LMC121.2	7798	1O	05:06:29.11	−70:31:03.4		23.4150.47			
...										

Seven candidates for ultra-low amplitude Cepheids in the LMC were found by Buchler *et al.* (2005). We stress that our sample of low amplitude variables not necessarily consist of Cepheids only. Such light curves can be a product of ellipsoidal or rotational modulation, or blending with other type of variable star.

The OIII-CVS is available in the electronic version only from the OGLE Internet archive:

http://ogle.astrouw.edu.pl/
ftp://ftp.astrouw.edu.pl/ogle/ogle3/OIII-CVS/lmc/cep/

The catalog is accessible through a user-friendly WWW interface or *via* FTP site. In the FTP the full list of our sample of classical Cepheids is given in the file ident.dat. Part of this file is shown in Table 1. All objects are arranged according to their right ascension. The Cepheids have designations of the form OGLE-LMC-CEP-NNNN, where NNNN is a four digit consecutive number. In the following columns of Table 1 we provide: Cepheid ID, OGLE-III field and the database number of star (consistent with the LMC photometric maps of Udalski *et al.* 2008b), mode of pulsation, RA and DEC coordinates for the epoch 2000.0 and cross-identifications of our objects with previously published catalogs of Cepheids in the LMC (see Section 5), successively: OGLE-II, MACHO, ASAS and General Catalogue of Variable Stars (GCVS). Last columns contain other designations taken from the GCVS.

Table 2

First 20 lines of the cepF.dat file

Cepheid ID	$\langle I\rangle$ [mag]	$\langle V\rangle$ [mag]	P [days]	σ_P [days]	$T_{\max}$ (HJD-2450000)	$A(I)$ [mag]	R_{21}	ϕ_{21}	R_{31}	ϕ_{31}
OGLE-LMC-CEP-0002	15.672	16.412	3.1181195	0.0000161	2171.23921	0.257	0.296	4.705	0.101	2.962
OGLE-LMC-CEP-0005	14.661	15.413	5.6120581	0.0000135	2171.78078	0.521	0.431	4.971	0.167	3.391
OGLE-LMC-CEP-0012	15.469	16.067	2.6601882	0.0000022	2162.43751	0.688	0.522	4.402	0.314	2.611
OGLE-LMC-CEP-0016	13.707	14.787	10.5064564	0.0015553	2157.57180	0.115	0.028	6.015	0.106	0.923
OGLE-LMC-CEP-0017	15.345	15.992	3.6772562	0.0000299	2169.48050	0.611	0.494	4.594	0.287	2.983
OGLE-LMC-CEP-0018	15.222	16.051	4.0478526	0.0000275	2165.39166	0.265	0.284	4.567	0.086	2.998
OGLE-LMC-CEP-0021	14.722	15.491	5.4579746	0.0000259	2165.34485	0.431	0.416	4.969	0.145	3.555
OGLE-LMC-CEP-0023	16.325	17.044	1.7018254	0.0000019	2164.75709	0.403	0.441	4.352	0.261	2.493
OGLE-LMC-CEP-0025	15.343	16.157	3.7334998	0.0000099	2165.69444	0.360	0.409	4.694	0.173	3.131
OGLE-LMC-CEP-0026	15.466	16.081	2.5706764	0.0000033	2164.25802	0.622	0.442	4.275	0.228	2.263
OGLE-LMC-CEP-0027	15.039	15.641	3.5229468	0.0000052	2165.27241	0.647	0.449	4.377	0.254	2.509
OGLE-LMC-CEP-0028	16.620	17.276	1.2629545	0.0000007	2171.08146	0.513	0.475	4.174	0.280	2.120
OGLE-LMC-CEP-0033	14.400	15.233	7.1807757	0.0000217	2160.83200	0.488	0.339	5.377	0.213	3.723
OGLE-LMC-CEP-0034	13.737	14.630	11.2546276	0.0000595	2180.63850	0.478	0.170	4.758	0.107	5.295
OGLE-LMC-CEP-0035	14.375	15.157	6.9436898	0.0000448	2165.30738	0.393	0.359	5.365	0.138	3.768
OGLE-LMC-CEP-0037	15.525	16.308	3.0669047	0.0000082	2165.55271	0.271	0.345	4.576	0.136	2.958
OGLE-LMC-CEP-0039	15.415	16.069	3.1477368	0.0000291	2164.95088	0.338	0.411	4.568	0.180	2.783
OGLE-LMC-CEP-0040	14.662	15.408	5.1651454	0.0000080	2182.37433	0.574	0.436	4.633	0.204	3.009
OGLE-LMC-CEP-0041	15.522	16.270	2.9106624	0.0000235	2165.81479	0.181	0.245	4.451	0.043	2.401
OGLE-LMC-CEP-0042	15.673	16.367	2.5770292	0.0000034	2183.19453	0.599	0.485	4.377	0.272	2.568

Files cepF.dat, cep1O.dat, cep2O.dat, cepF1O.dat, cep1O2O.dat, cep1O3O.dat, cepF1O2O.dat, and cep1O2O3O.dat list basic parameters of the single-, double- and triple-mode Cepheids with the appropriate modes excited. For single-mode objects the consecutive columns contain: intensity mean magnitudes in the I and V bands, periods in days and their uncertainties, moments of the zero phase corresponding to maximum light, amplitudes in the I-band, and Fourier parameters R_{21}, ϕ_{21}, R_{31}, ϕ_{31} derived for the I-band light curves. For double-mode and triple-mode pulsators the format of tables is longer including additional periodicities. First rows of the file cepF.dat are shown in Table 2.

The file remarks.txt contains additional information on some Cepheids. We provide here remarks about uncertain classification, interesting features as additional variability, variable mean magnitudes or amplitude modulation, and information about differences compared to other catalogs (for example different periods). Directory phot/ contains I- and V-band OGLE photometry of the stars in our catalog. If available, OGLE-II data are merged with the OGLE-III data. Finally, the directory fcharts/ contains finding charts of all objects. These are the $60'' \times 60''$ segments of the I-band DIA reference images, oriented with N up, and E to the left.

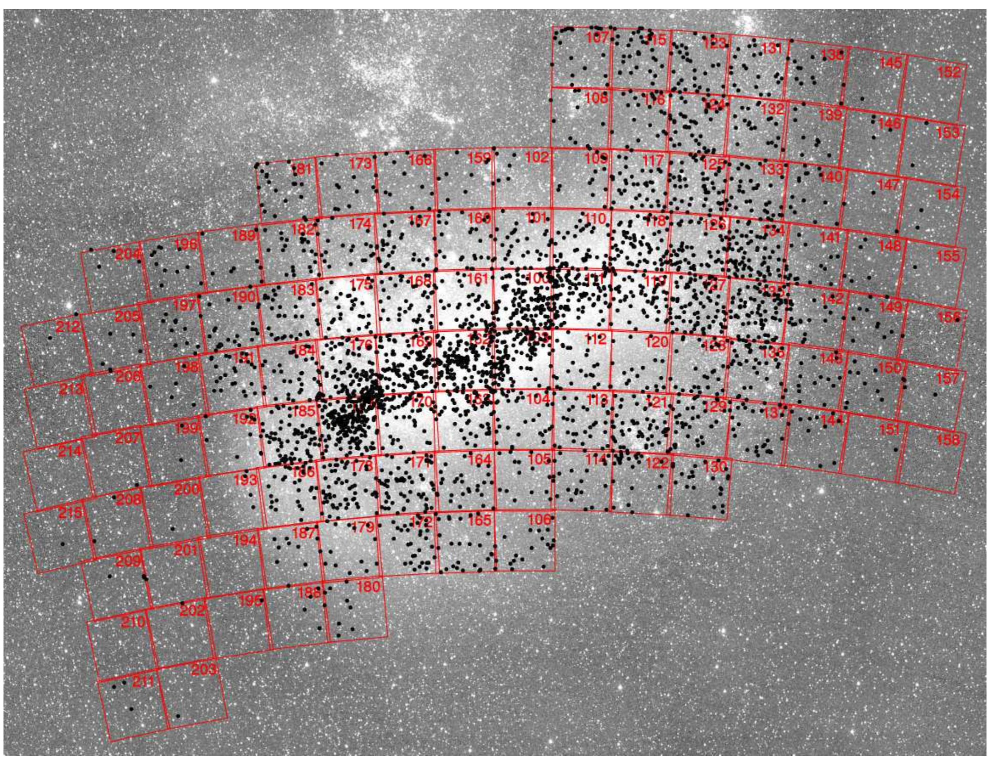

Fig. 4. OGLE-III fields in the LMC. Dots indicate positions of classical Cepheids from the OIII-CVS catalog. The background image of the LMC is originated from the ASAS wide field sky survey.

Fig. 4 shows the spatial distribution of the classical Cepheids in the LMC. The picture of the LMC was taken by the ASAS-3 wide field sky survey (Pojmański 1997). Illustrative light curves of Cepheids pulsating in the fundamental, first and second overtone modes are shown in Fig. 1. One can notice the Hertzsprung progression (Hertzsprung 1926) for long period fundamental-mode pulsators, *i.e.*, a bump moving toward earlier phases with increasing periods.

5. Cross-Identification with Previous Catalogs

The catalog includes matches of our objects with previously published list of classical Cepheids in the LMC. We queried the following catalogs: OGLE-II catalogs of Cepheids in the LMC (Udalski *et al.* 1999d, Soszyński *et al.* 2000), on-line MACHO Variable Star Catalog†, the extragalactic part of the General Catalogue of Variable Stars (Artyukhina *et al.* 1995), and ASAS Catalog of Variable Stars‡ (Pojmański 2002). In our sample of Cepheids 2367 stars were already published in any of these catalogs, 994 objects are new detections.

With the aim of testing the completeness of our catalog we carefully checked all objects not present in our list, but potentially covered by the OGLE-III fields. Compared to the OGLE-II catalog of Cepheids in the LMC published by Udalski *et al.* (1999d – single-mode Cepheids) and Soszyński *et al.* (2000 – double-mode Cepheids) we missed 8 classical Cepheids (not counting 16 objects saturated in the OGLE-III data). Five of these Cepheids are members of LMC clusters and severe crowding affected the OGLE-III photometry. The three remaining objects were close to the edges of the fields and were affected by a small number of observations. We supplemented our catalog with these missing objects.

The MACHO project released the list of about 1800 Cepheids in the LMC. 1721 of them could potentially be found in the OGLE-III fields. We did not find counterparts for 15 variables. Lack of five of these stars can be explained by a small number of points at the field edges or problems with the photometry in dense regions of the sky. The other objects were classified by us as different type of variable stars, usually eclipsing binaries.

The General Catalogue of Variable Stars contains 873 stars classified as DCEP or DCEPS and potentially present in our fields in the LMC. We performed an extensive searching for the counterparts of these stars in our sample. In a number of cases the cross-identification between our sample and the GCVS was uncertain, because of a large discrepancy (sometimes larger than $2'$) in coordinates of the objects. Sometimes, the stars were positionally coincident, but the periods disagreed. For many of these objects we noticed that the period provided in the GCVS was an alias of the true period. One missing object, LMC V0477 (DV53), we classified as eclipsing or ellipsoidal binary. Another star, LMC V0857 (HV 2284), was recog-

† *http://wwwmacho.mcmaster.ca/*

‡ *http://www.astrouw.edu.pl/asas/*

nized as Galactic RR Lyr star. LMC V0566 (HV 12509) is likely a type II Cepheid in the eclipsing binary system.

We found no counterparts for nine stars classified as classical Cepheids in the GCVS, namely LMC V0224 (HV 12496), V0452 (DV44), V1620 (HV 13018), V2175 (HV 5767), V2329, V2368 (HV 13032), V3972, V4366, and V4441 (HV 12909). Since periods and coordinates provided by the GCVS are sometimes erroneous, it is possible that these objects are present in our sample, but each case should be directly checked using finding charts from the literature. Such investigation should also reveal possible Cepheids which stopped pulsating.

6. Basic Parameters

The periods of variable stars and uncertainties of periods provided in the catalog were calculated with the TATRY program using multiharmonic periodogram of Schwarzenberg-Czerny (1996). To determine mean luminosities, amplitudes and Fourier parameters, each of the light curve was fitted by a Fourier series of the order depending on the shape and scatter of the light curve. The number of harmonics (maximum 12) was adjusted to minimize the value of χ^2 per degree of freedom. In this procedure we used the program J-23 written by T. Mizerski.

The *VI* intensity mean magnitudes were derived by integrating the light curves converted to intensity units and transforming the result back to the magnitude scale. The amplitudes provided with the catalog are the differences between the maximum and minimum values of the function fitted to the light curves. Fourier parameters – amplitude ratios $R_{k1} = A_k/A_1$ and phase differences $\phi_{k1} = \phi_k - k\phi_1$ (Simon and Lee 1981) – were derived using the same method of Fourier decomposition. For light curves with insignificant higher harmonics the amplitude ratios are equal to zero, while the appropriate phase differences are not defined.

Fig. 5 shows Fourier parameters R_{21}, ϕ_{21}, R_{31}, and ϕ_{31} of the *I*-band light curves plotted against $\log P$. For clarity fundamental-mode and overtone Cepheids are presented in separate panels. Fourier coefficients are widely used tool for quantitative description of the structure of Cepheid light curves. Complex pattern visible in the diagrams reflects the Hertzsprung progression. The minimum of R_{21} at $P \approx 10$ days for fundamental-mode Cepheids is interpreted as a signature of 2:1 resonance between the fundamental and the second overtone mode of pulsation (Andreasen and Petersen 1987). In the vicinity of 10 days periods the ϕ_{21} parameter rises sharply to 2π and appears again in the lower part of the diagram, what is caused by rotation of ϕ_{21} modulo 2π. Note that such sharp feature in ϕ_{21} is not observed for some of the Cepheids around this period, but all of them cross the line $\phi_{31} = 0$ at $P \approx 10$ days.

Similar behavior seem to appear twice for the first-overtone pulsators – at periods ≈ 0.35 days and ≈ 3 days. The second feature is interpreted as the signature of 2:1 resonance between the first and fourth overtones (Antonello and Poretti

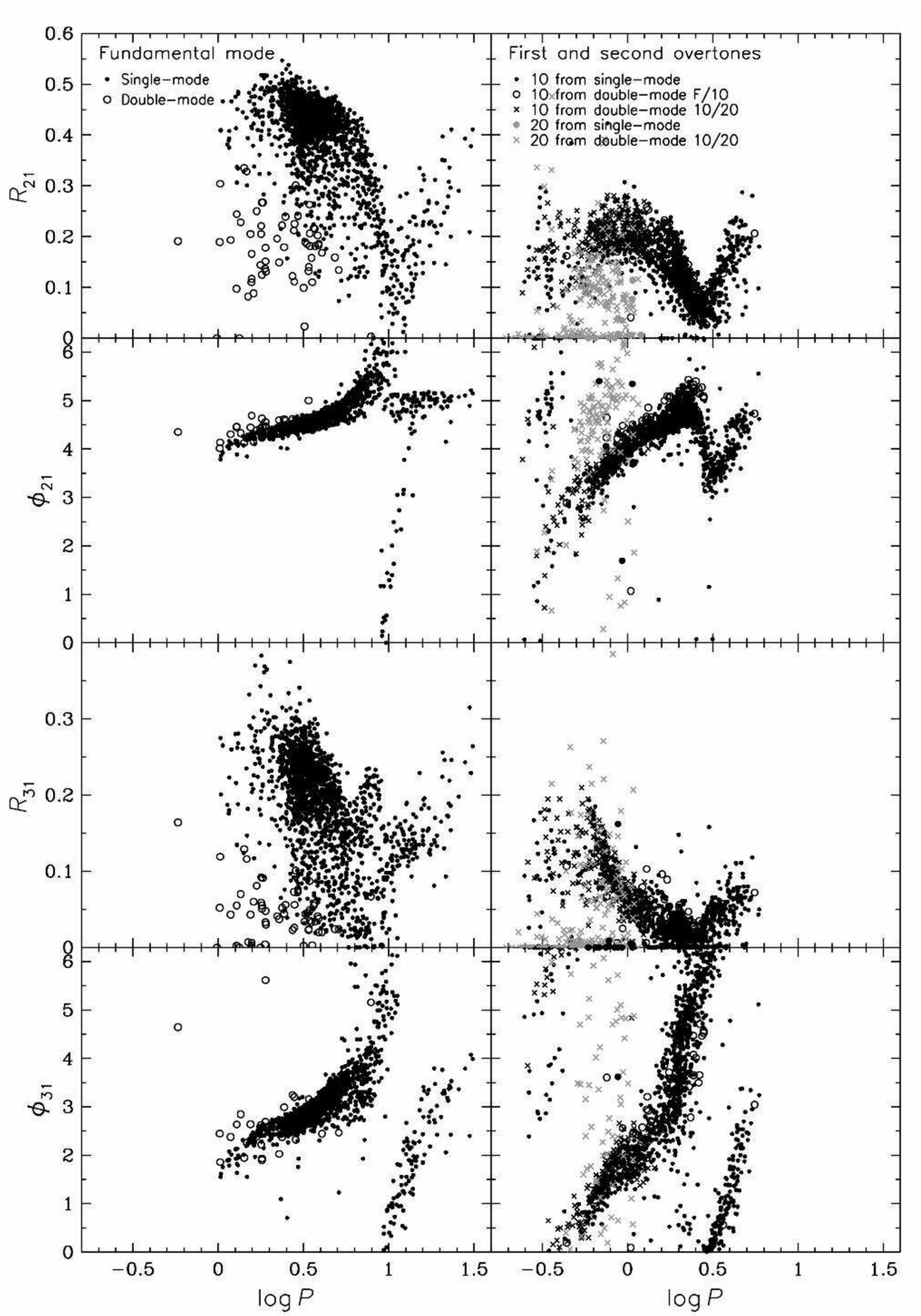

Fig. 5. Fourier parameters of the fundamental-mode (*left panels*) and overtone (*right panels*) Cepheids.

1986). The short-period discontinuity can be explained by a presence of the 2:1 resonance between the first and fifth overtones in stars with masses of about 2.5 $M_{\odot}$ (W. Dziembowski, private communication).

7. Period-Luminosity Relation

Period–luminosity relation of classical Cepheids plays a crucial role as an indicator of the cosmic distance scale. The LMC is of special interest in this field, because the extragalactic distances are calibrated with the distance to this galaxy. Classical Cepheids found during the second phase of the OGLE survey in the LMC were widely used in various programs aiming at distance determinations, *e.g.,* HST Key Project (Freedman *et al.* 2001) or Araucaria Project (Gieren *et al.* 2004).

The PL diagrams in the V and I magnitudes and in the reddening-free Wesenheit index $W_I = I - 1.55(V - I)$ (Madore 1982) are shown in Fig. 6. It is striking that substantial fraction of points in the first two plots are located considerably below the mean PL relations, but these stars generally follow the narrow sequences in the period – Wesenheit index plane. We interpret such behavior as an effect of interstellar extinction – very variable from star to star. Considerable reddening for some Cepheids is visible on the color–magnitude diagram plotted in Fig. 7.

We also carefully checked the stars that do not obey the PL relations in the $\log P$–W_I plane. In the majority of these cases this discrepancy can be explained by blending with other star unresolved in our data. Most of the Cepheids with superimposed additional type of variations (including Cepheids with eclipsing modulations) do not match the period-W_I laws. Notice that the PL sequence for the longest-period fundamental-mode Cepheids seem to be more scattered than for the shorter-period variables. It may be due to saturation effects, but the definitive answer will be given after publication of the OGLE shallow survey to the LMC.

The PL relations provided below are not compensated for interstellar extinction. We leave it to the reader to de-redden magnitudes using either average extinction correction for the whole LMC or individual values for each object. We also take no account for possible break of the linearity suggested for the PL relation of fundamental mode Cepheids (see Ngeow *et al.* 2008 and references therein). We expect that our catalog will be used many times to establish PL relations, and various subtle effects will be taken into consideration.

The least squares solution with 3σ clipping yields the following PL relations for single-mode fundamental-mode classical Cepheids:

$$\begin{aligned}
V &= -2.762(\pm 0.022)\log P + 17.530(\pm 0.015) \qquad \sigma = 0.22 \text{ mag}\\
I &= -2.959(\pm 0.016)\log P + 16.879(\pm 0.010) \qquad \sigma = 0.15 \text{ mag}\\
W_I &= -3.314(\pm 0.009)\log P + 15.893(\pm 0.006) \qquad \sigma = 0.08 \text{ mag}
\end{aligned}$$

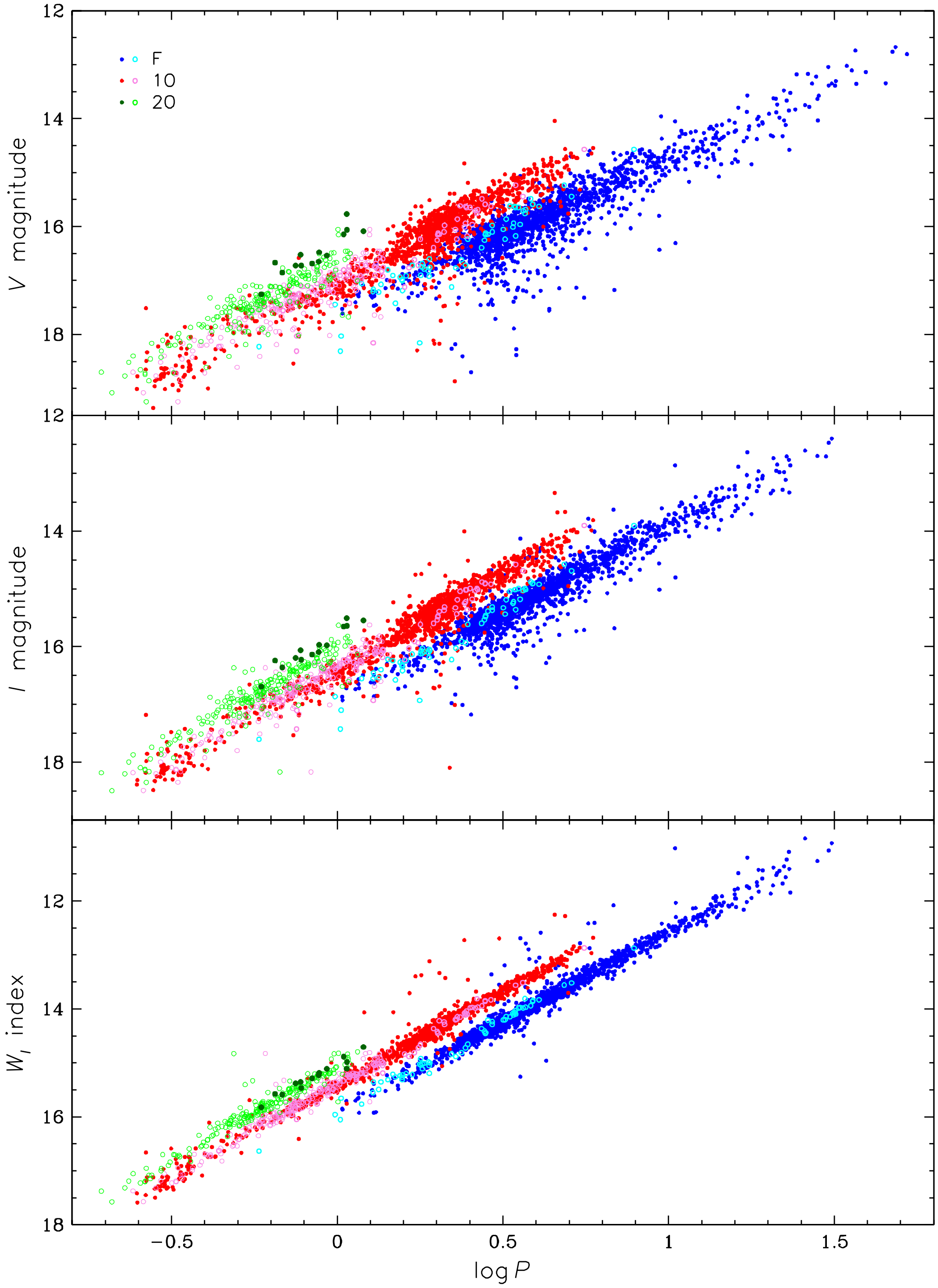

Fig. 6. Period–luminosity diagrams for classical Cepheids in the LMC. Blue and cyan points show fundamental-mode pulsators, red and magenta – first-overtone, green – second overtone. Solid dots are single-mode Cepheids, while empty circles represent double-mode pulsators (two points per star).

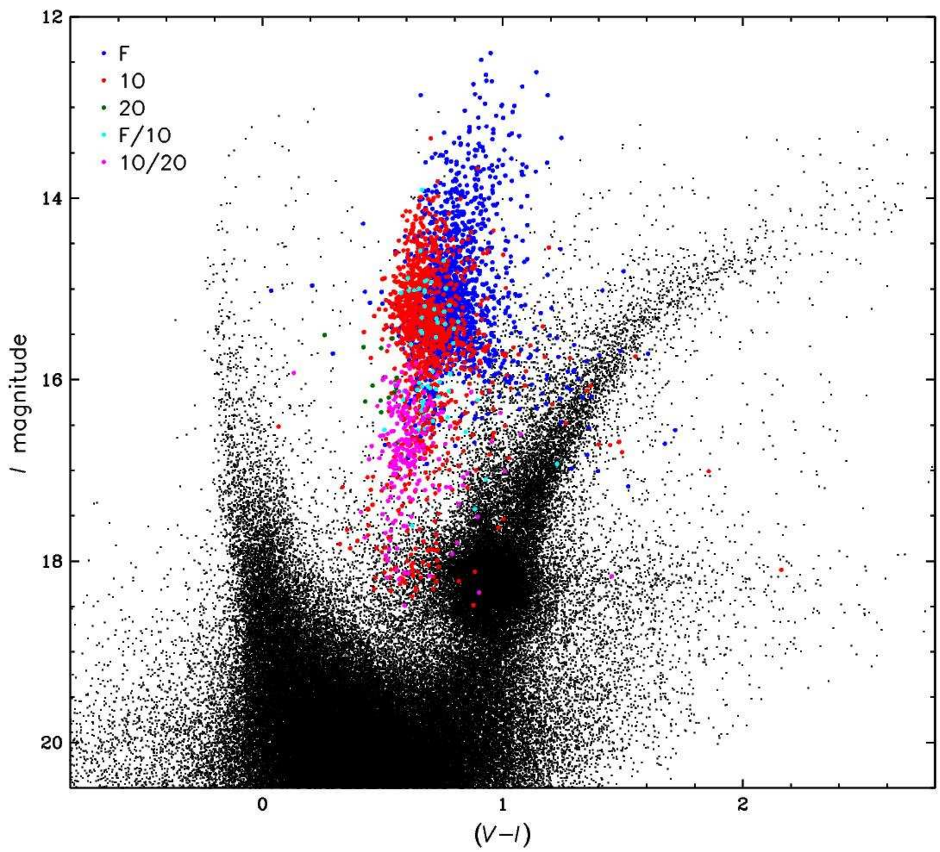

Fig. 7. Color–magnitude diagram for classical Cepheids in the LMC. In the background stars from the subfield LMC100.1 are shown. The significant number of very red Cepheids are clearly located to the red side of the respective instability strips for the various pulsation modes indicating that large reddening is not unusual in the LMC.

and for the first-overtone mode:

$$\begin{aligned} V &= -3.194(\pm 0.026)\log P + 17.046(\pm 0.009) \qquad \sigma = 0.23 \text{ mag} \\ I &= -3.297(\pm 0.017)\log P + 16.405(\pm 0.006) \qquad \sigma = 0.16 \text{ mag} \\ W_I &= -3.451(\pm 0.009)\log P + 15.398(\pm 0.003) \qquad \sigma = 0.07 \text{ mag.} \end{aligned}$$

The slopes of the PL relations for fundamental-mode Cepheids agree within 1σ with previous determinations by Udalski *et al.* (1999c)[§], and Fouqué *et al.* (2007). Of course, in the V and I domains we can only compare the slopes, because we did not applied the reddening correction, but in the W_I extinction-free index we can consider both, the slope and the zero point, of the PL relation. There is larger discrepancy ($> 2\sigma$) in the zero point of the $\log P$–W_I relation. We also obtained

[§]updated coefficients are available from:
ftp://ftp.astrouw.edu.pl/ogle/ogle2/var_stars/lmc/cep/catalog/README.PL

somewhat larger scatter of the PL relations in the OGLE-III sample, what can be explained by the inclination of the LMC disk in respect to the line of sight. The OGLE-II fields covered only the central parts of the LMC, what kept this effect much smaller. It is important to note that Udalski *et al.* (1999c) and Fouqué *et al.* (2007) used the same definition of the Wesenheit index as we did, but this definition depends on the adopted reddening law. Using different coefficient in the Wesenheit index results in different slope and zero point of the fitted PL relation.

The agreement in slopes is much worse for first-overtone Cepheids, although still within 3σ. We suspect that a considerable number of very short-period first-overtone pulsators, not present in the OGLE-II sample of Cepheids, which changed the fitted function could be an origin of this discrepancy. The non-linearity of the PL relation may take place for the first-overtone Cepheids, with the break at $P_1 \approx 0.5$ days.

8. Summary

In this paper we present the largest catalog of classical Cepheids in the LMC and probably the largest sample of such stars identified to date in any environment. Our list of Cepheids is supplemented by the high quality, long-term standard photometry enabling precise analysis of these stars. These data are ideal for studying many fundamental problems, such as interpretation of the pulsational and evolutionary models of Cepheids, non-radial oscillations in the pulsating stars, possible non-linearity of the PL relation, structure and history of the LMC.

The catalog contains very rare objects, such as Cepheids with three radial modes excited, 1O/3O double-mode Cepheids, single-mode second-overtone pulsators, Blazhko Cepheids, eclipsing binary systems containing Cepheids including system of two Cepheids eclipsing each other. Our data show that first-overtone classical Cepheids and high amplitude δ Sct stars follow continuous PL relation. Distribution of the Fourier parameters suggests that the internal resonance between radial modes may occur twice for the first-overtone pulsators: for periods of about 0.35 days and 3 days. The PL relation for first-overtone Cepheids is possibly non-linear, with a discontinuity in the slope around $P = 0.5$ days.

In the next parts of the OIII-CVS we will present other members of the Cepheid family: type II Cepheids, anomalous Cepheids, HADS and RR Lyr stars. It is possible that the list of classical Cepheids described in this paper will be supplemented with additional objects of this type detected during further analysis.

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